Institution: University of Cambridge
Unit of Assessment: 9 – Physics
Title of case study: Cavendish Kinetics: University of Cambridge spin out improves the energy efficiency and data transfer speed of mobile phones
Period when the underpinning research was undertaken: 2000 to 2007

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor Charles G. Smith	Professor of Semiconductor Physics	1989 to present

Period when the claimed impact occurred:
1 August 2013 – 31 July 2020

Is this case study continued from a case study submitted in 2014? Y

Summary of the impact (indicative maximum 100 words)

Cavendish Kinetics is a University of Cambridge spin out based on the research of Professor Charles G. Smith and his team in developing digital variable capacitor products for mobile phones. These capacitors, used in 35 million phones worldwide, increase the speed at which data can be sent and received; reduce the power required to send and receive signals, increasing efficiency by 100% versus broadband antennas; and significantly reduce CO_2 emissions by an estimated 2 million Kg of CO_2 emissions per year. The economic impact of Cavendish Kinetics can be summarised as follows:

- Total turnover (from March 2014 to March 2019) of USD17.149 million
- A workforce of 52 (an increase of 19 within the period)
- In October 2019, Qorvo Inc fully acquired Cavendish Kinetics for over USD300 million (USD300,768,000)

2. Underpinning research (indicative maximum 500 words)

Research led by Professor Charles G. Smith in the Department of Physics at the University of Cambridge has resulted in the development of micro-electromechanical (MEMS) switches for mobile phones which overcome the performance, production and cost challenges presented by the existing technology.

Problem

Around 2011, 4G was introduced for smart phones allowing faster data transmission because data could be split between more than one frequency band, both during upload and download. However, this brought with it new challenges. The frequency bands used by 4G are specific according to the region of the globe so one phone may need to work at over 50 different frequencies (something that will increase with 5G where new bands will be added). As there is no room in the phone to house more than one antenna, phone manufacturers use variable capacitors connected to the antenna to tune them to work at different frequencies. In the past this was achieved with gallium arsenide switches (GaAs) connected to fixed capacitors. This combination is expensive, firstly because the switches need to operate up to several gigahertz without distorting the signal or damping the resonance; and secondly, because they must also be extremely linear to avoid producing harmonic signals which swamp the receiver. Cavendish Kinetics, which Smith spun out from the university in 1994, and for whom he continued to work until its acquisition in 2019, had initially focussed on developing MEMS switches for non-volatile memory applications. By 2014, Cavendish Kinetics had changed its product from a memory device to a digital variable capacitor device. The goal was to replace the expensive GaAs switches used as variable capacitors in mobile phones with low cost micro-electromechanical (MEMS) alternatives. This goal was made possible by the detailed long-range research on understanding the properties of cantilever MEMS switches performed jointly from 2000 by the Department of Physics at the University of Cambridge and Cavendish Kinetics.

Key Findings of the Research

Research in the Department of Physics has pushed for the development of the smallest possible MEMS devices which allow switches to operate at low-voltages and high-speeds and have a large ratio (greater than five orders of magnitude) between the on and off resistance. This ensures very low leakage of power when the switch is off and no unwanted dissipation of power when the switch is on [R1]. Amongst the key findings of this research are technological developments relating to control of contact roughness, cantilever switching, cantilever design and the use of complementary metal–oxide–semiconductor (CMOS) deposition techniques. Smith's research has explained how contact roughness alters with the contact adhesion force in nano-switches and how this relates to contact resistance changes. This is an important design parameter because the roughness of the contact is related to the contact area [R1, R2, R3]. If this becomes too large the switches stick on, while if it is too small the resistance is too high. At high powers the voltage drop across the contact results in an increased force and this can also change the contact area leading to unwanted changes in the device properties including non-linearities that can lead to harmonic generation in radio frequency (RF) devices which can swamp the receiver. Understanding how to control this contact area and roughness ensures highly linear switches can be made.

For MEMS switches to compete with semiconductor alternatives they must actuate at low voltages and switch many times before failure. Smith's research demonstrated how controlling the contact area allowed cantilevers to switch over one billion times: about the number of times switches need to be operated to tune a mobile phone during its lifetime [R4]. His research also identified an important design technique for MEMS by demonstrating how controlling the cantilever shape using the sacrificial layer enables bump size to be controlled as well as enabling enhanced cantilever strength with minimal addition of mass (important for switching speed) [R5]. Getting the switching speed down was required so that tuning in phones could be achieved fast enough not to be noticeable to the user. Joint research [R1] also showed that the MEMS devices could be encapsulated using CMOS deposition techniques within the foundry where the sacrificial etch and cavity seal are performed in the same tool. Production on silicon in a standard CMOS facility greatly reduces the final cost of the product compared to the GaA and Silicon on Insulator switch competition. Up until then, MEMS switches were bonded into expensive hermetically sealed packages often costing between two and five times the chip cost. Being able to etch out the sacrificial layer and seal the cavity in the same tool without bringing it up to air also ensures a very clean contact to the switch.

Smith's research therefore allowed the development of fast, low cost MEMS switches with excellent RF switching characteristics that could be switched billions of times before failure. This opened up a large market for the tuning of RF signals in mobile devices as these switches had better RF characteristics than the existing technology and the ability to be manufactured at a lower cost.

3. References to the research (indicative maximum of six references).

*All research outputs marked with * have been through a rigorous peer-review process.*
Reference R1 was a peer reviewed conference paper.

R1 Smith, **C.G**., van Kampen, R., Popp, J., Lacy, D., Pinchetti, D., Renault, M., Joshi, V., Beunder, M. A. (2007). Nanomechanical cantilever arrays for low-power and low-voltage embedded non-volatile memory applications. MEMS/MOEMS Components and Their Applications IV 6464, 646406 (2007). doi.org/10.1117/12.698964

R2* Teh, W. H., & **Smith, C. G.** (2003). Reversible electrostatic control of micromechanical structure tunneling characteristics. J APPL PHYS, 94(7), 4614-4618. doi:10.1063/1.1606854

R3* Teh, W. H., Luo, J. K., Graham, M. A., Pavlov, A., & **Smith, C. G**. (2003). Near-zero curvature fabrication of miniaturized micromechanical Ni switches using electron beam cross-linked PMMA. Journal of Micromechanics and Microengineering, 13(5), 591-598. doi:10.1088/0960-1317/13/5/309

R4* Teh, W. H., Luo, J. K., Graham, M. R., Pavlov, A., & **Smith, C. G**. (2003). Switching characteristics of electrostatically actuated miniaturized micromechanical metallic cantilevers. J VAC SCI TECHNOL B, 21(6), 2360-2367. doi:10.1116/1.1620515

R5* Teh, W. H., Liang, C. T., Graham, M., & **Smith, C. G**. (2003). Cross-linked PMMA as a low-dimensional dielectric sacrificial layer. J MICROELECTROMECH S, 12(5), 641-648. doi:10.1109/JMEMS.2003.817891

Grants

Micro-mechanics applied to CMOS devices. Funded by Cavendish Kinetics Ltd. 01 November 1999 to 01 November 2002: GBP67,040

Semiconductor Quantum Nanoelectronics: Physics and Applications. Funded by EPSRC GR/R54224/01. 01 October 2001 to 30 September 2005: GBP3,837,487
Principal Investigator: Pepper, Professor Sir M. Co Investigators: Ford, Professor CJB. **Smith, Professor CG.** Linfield, Professor EH. Davies, Professor AG. Jones, Dr G. Thomas, Dr K. Ritchie, Professor DA. Barnes, Professor C.

4. Details of the impact (indicative maximum 750 words)

Smith's research in the Department of Physics provided the foundation for the development of the Cavendish Kinetics digital variable capacitor. These capacitors improve mobile phone performance, reduce energy consumption, and therefore significantly reduce mobile device CO_2 emissions. Combined with the low cost of production, these benefits have resulted in the rapid growth of Cavendish Kinetics into a prize winning multi-million-dollar company.

Growth of Cavendish Kinetics into prize winning multi-million-dollar company

In 2013, Cavendish Kinetics started to work with TowerJazz, a partner CMOS manufacturer which ported the MEMS process Cavendish Kinetics had developed to their Tower Jazz fabrication facility in California [E1]. Tower Jazz uses the Cavendish Kinetics MEMS process to make devices which Cavendish Kinetics then sells to its customers. In June 2014, Cavendish Kinetics Ltd demonstrated MEMS devices could be cycled 50 billion times without failure [E2] leading to a USD7 million venture capital round in November 2014 [E3A]. In August 2015, the company completed a USD36 million investment round to grow their customer base and develop a wider range of MEMS products [E3B;E3C]. By February 2017, TowerJazz and Cavendish Kinetics announced they had obtained 40 smartphone handset design wins, including the 2016 Samsung Galaxy A8 [E4]. In 2017 Cavendish Kinetics won the Linley Group Choice Award which recognized the top semiconductor products of 2016. Cavendish Kinetics won for best Mobile Chip. The other award winners included big industry names such as Intel and Qualcomm [E5].

Economic Impact

The success of Cavendish Kinetics technology led to QORVO Inc. (formerly Triquint Inc.) investing in Cavendish Kinetics and agreeing an option to acquire the company outright with an offer of USD300 million minus actual net debt, plus a value based on revenue if the company achieved release of an agreed specified product [E6]. In this REF period Cavendish Kinetics greatly increased its sales, growing its customer base and increasing its turnover from USD310,235 in the year to end of March 2015 to USD7.307 million in the year to March 2019 [E7A]. Over that period from March 2014 to March 2019, the total turnover at Cavendish Kinetics was USD17.149 million [E7A]. The total workforce in 2019 was 52 people (an increase of 19 since 2014) [E7B]. Estimates show "the company has shipped over 35 million units and today counts as its clients ZTE, Oppo, Gionee, Coolpad, Xiaomi, and Samsung." [E8]. In October 2019, Qorvo Inc fully acquired Cavendish Kinetics for for over USD300 million (USD300,768,000) [E7C].

Improving Performance: reducing phone energy consumption and increasing data transfer rates

Cavendish Kinetics digital variable capacitors are used in 35 million phones worldwide [E8]. Revenue from sales increased 53% between March 2018 and March 2019 [E7D], and this rapid growth was driven by the low cost and high technical specifications of the product.

The Cavendish Kinetics digital variable capacitors offer two major performance advantages in terms of switching and tuning which result in increased data transfer rates and reduced energy consumption. An important technique used for increasing the data transfer rates in a phone involves sending signals out at one frequency while receiving signals at a different frequency (called multiple in multiple out or MIMO). If signals are being sent out at high power (one Watt) and being received at another frequency at one micro Watt, any non-linearity on the switch causes the output power which is a million times larger than the receiver signal to generate signals at harmonics that may overlap with the input frequency swamping the input amplifier. The Cavendish Kinetics switch product solves this problem by removing the unwanted non-linearities.

An additional problem in mobile phones comes from the proximity of your hand or your head to the antenna causing a change in the resonant frequency of the circuit by locally changing the capacitance seen by the antenna. With a Cavendish Kinetics digital variable capacitor this change can be tuned out allowing far better matching of the antenna signal with the amplifier.

Both these advantages reduce the power required to send and receive signals. For example, the Cavendish Kinetics' SmarTune Antenna Tuner (which can be used in mobile phones, tablets and wearable devices, and which fits in a $2mm^2$ Wafer-level-Chip-ScalePackage) achieves a 100% increase in efficiency at 700 MHz versus broadband antennas [E9]. It also allows the use of bands that are closer together so that more data can be sent and received more quickly. Cavendish Kinetics tuning allows frequency tuning from 600MHz to 900MHz with a quality factor (Q) greater than 200 allowing multiple bands to be tuned in and out over this bandwidth, thereby increasing data transfer speeds [E9]. A comparable product such as the ST Parascan tunable integrated capacitor, for example, has a Q of just 55 at 700MHz [E10].

Environmental Impact: reducing CO_2 emissions

In addition to mobile phone performance improvements, the reduction in power required as a result of using the Cavendish Kinetics switch could also potentially save significant CO_2 emissions for the 35 million phones using Cavendish Kinetics digital variable capacitors [E9].

Sandrine Pfister, Impact and Financial Manager at Quadia investment suggests that: "Cavendish Kinetics' products improve battery life by 40% with more efficient antenna function, thus reducing energy use, diminishing CO_2 emission and creating higher quality phone calls. There are more than 1.5 billion smartphones sold each year, with 5 billion people having a mobile device worldwide. Addressing the entire smartphone market, CK's products could save up to 280 million kWh/year" [E8].

Based on the figures in the government's methodology paper for emission factors (which estimates that UK electricity produces 0.31 $KgC0_2$/kWh) [E11], this suggests that Cavendish Kinetics technology is currently saving 6.5 million kWh/year for the 35 million phones which use it, resulting in a reduction of approximately 2 million Kg of CO_2 emissions per year.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[E1]. TowerJazz and Cavendish Kinetics Collaborate https://towerjazz.com/wp-content/uploads/2018/08/pr06062013.pdf

[E2]. Cavendish Kinetics sets new industry benchmark https://towerjazz.com/wp-content/uploads/2018/08/TowerJazz_PR_20140603-2.pdf

[E3]. Investment Funding (collated document):

E3A Cavendish Kinetics raises USD7 million https://www.wsj.com/articles/DJFVW00120141111eabbask5u

E3B Cavendish Kinetics raises USD36 million https://www.eenewsanalog.com/news/qorvo-takes-strategic-stake-mems-vendor-cavendish

E3C Cavendish Kinetics raises USD10 million http://www.eetimes.com/document.asp?doc_id=1259675

[E4]. Cavendish Kinetics smartphone wins https://towerjazz.com/2017/02/28/0228/

[E5]. Cavendish Kinetics wins the Linley Group Choice Award https://www.linleygroup.com/press_detail.php?The-Linley-Group-Announces-Winners-of-Annual-Analysts-Choice-Awards-85

[E6]. QORVO Inc. agree option to acquire company outright (see page 24 of PDF) https://www.sec.gov/Archives/edgar/data/1604778/000160477815000109/exhibit2120151003.htmSee section 7 page 19

[E7]. Collated document – financial reports for Cavendish Kinetics and Qorvo Inc.

E7A For turnover figures see pages 9, 40, 66, 107 and 153 of E7 PDF

E7B For workforce figures see pages 18 and 167 of E7 PDF

E7C For acquisition figure see page 234 of E7 PDF

E7D For revenue from sales increase see page 147 of E7 PDF

[E8]. The company has shipped over 35 million units http://www.quadia.ch/uploads/images/investment/20191115%20-%20Quadia%20-%20Exit%20Announcement_Cavendish.pdf

[E9]. Product Brief for Cavendish Kinetics Smartune Antenna Tuners https://www.cavendish-kinetics.com/wp-content/uploads/2016/07/PB32CKxxxR_v2.2.pdf

[E10]. See Table 3, Page 3 of Data Sheet for Parascan™ tunable integrated capacitor https://www.st.com/resource/en/datasheet/stptic-27l2.pdf

[E11]. Methodology paper for emission factors. See Table 7, Page 26 of https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/726911/2018_methodology_paper_FINAL_v01-00.pdf